Self-Organisation & Autonomy
An Introduction

Autonomous Systems
Sistemi Autonomi

Andrea Omicini
after Luca Gardelli
andrea.omicini@unibo.it

Dipartimento di Informatica – Scienza e Ingegneria (DISI)
Alma Mater Studiorum – Università di Bologna

Academic Year 2015/2016

Outline

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Intuitive Idea of Self-Organisation

- Self-organisation generally refers to the internal process leading to an increasing level of organisation
- *Organisation* stands for relations between parts in term of structure and interactions
- *Self* means that the driving force must be internal, specifically, distributed among components

History of Self-Organisation

- The idea of the spontaneous creation of organisation can be traced back to René Descartes
- According to the literature, the first occurrence of the term Self-Organisation is due to a 1947 paper by W. Ross Ashby [Ash47]
- Ashby defined a system to be self-organising if it changed its own organisation, rather being changed from an external entity

Elements of Self-Organisation

Increasing order — due to the increasing organisation

Autonomy — interaction with external world is allowed as long as the control is not delegated

Adaptive — suitably responds to external changes

Dynamic — it is a process not a final state

Self-Organisation in Sciences

- Initially ignored, the concept of self-organisation is present in almost every science of complexity, including
  - physics
  - chemistry
  - biology and ecology
  - economics
  - artificial intelligence
  - computer science

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History of Emergence

- Emergence is generally referred as the phenomenon involving global behaviours arising from local components interactions
- Although the origin of the term emergence can be traced back to Greeks, the modern meaning is due to the English philosopher G.H. Lewes (1875)
- With respect to chemical reactions, Lewes distinguished between *resultants* and *emergents*
    - Resultants are characterised only by their components, i.e. they are reducible
    - Conversely, emergents cannot be described in terms of their components

Definition of Emergence

- We adopt the definition of emergence provided in [Gol99]

  Emergence [..] refers to the arising of novel and coherent structures, patterns, and properties during the process of self-organisation in complex systems. Emergent phenomena are conceptualised as occurring on the macro level, in contrast to the micro-level components and processes out of which they arise.

Emergence vs. Holism

- Emergence is often, and imprecisely, explained resorting to *holism*
- Holism is a theory summarisable by the sentence *the whole is more than the sum of the parts*
- While it is true that an emergent pattern cannot be reduced to the behaviour of the individual components, emergence is a more comprehensive concept

Properties of Emergent Phenomena

Novelty — unpredictability from low-level components

Coherence — a sense of identity maintained over time

Macro-level — emergence happens at an higher-level w.r.t. to components

Dynamism — arise over time, not pre-given

Ostensive — recognised by its manifestation

Requirements for Emergency

Emergence can be exhibited by systems meeting the following requirements

Non-linearity — interactions should be non-linear and are typically represented as feedback-loops

Self-organisation — the ability to self-regulate and adapt the behaviour

Beyond equilibrium — non interested in a final state but on system dynamics

Attractors — dynamically stable working state

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Definition of Self-Organisation

Widespread definition of Self-Organisation by [CDF+01]

Self-organisation is a process in which pattern at the global level of a system emerges solely from numerous interactions among the lower-level components of the system. Moreover, the rules specifying interactions among the system's components are executed using only local information, without reference to the global pattern.

- It is evident that the authors conceive self-organisation as the source of emergence
- This tendency of combining emergence and self-organisation is quite common in biological sciences
- In the literature there is plenty of misleading definitions of self-organisation and emergence [DWH05]

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Natural Systems

- Natural systems can be broadly as [DGK11]
  - physical systems
  - biological systems
  - social systems

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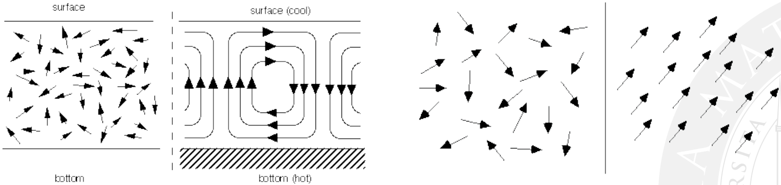
Physics and Chemistry

- Theory of self-organisation were originally developed within Physics and Chemistry
- Most typical features included
  - when the system reaches a *critical threshold*, an immediate change occurs
  - self-organisation can be observed *globally*

Self-Organisation of Matter

- Self-organisation of matter happens in several fashion
- In magnetisation, spins spontaneously align themselves in order to repel each other, producing and overall strong field
- Bénard cells is a phenomena of convection where molecules arrange themselves in regular patterns because of the temperature gradient

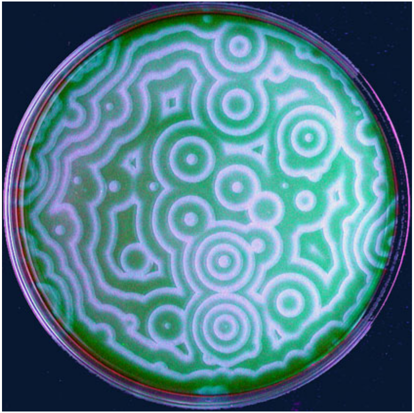


The left hand side picture displays Bénard cells.
The right hand side picture displays magnetisation.

Belousov-Zhabotinsky Reaction I

- Discovered by Belousov in the 1950s and later refined by Zhabontinsky, BZ reactions are a typical example of far-from-equilibrium system
- Mixing chemical reactants in proper quantities, the solution colour or patterns tend to oscillate
- These solutions are referred as *chemical oscillators*
- There have been discovered several reactions behaving as oscillators

Belousov-Zhabotinsky Reaction II



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Living Organisms

- Self-organisation is a common phenomenon in subsystems of living organisms
- An important field in biological research is the determination of invariants in the evolution of living organisms
  - in particular the spontaneous appearance of order in living complex systems due to self-organisation
- In biological research, self-organisation essentially means the global emergence of a particular behaviour or feature that cannot be reduced to the properties of individual system's components—such as molecules and cells

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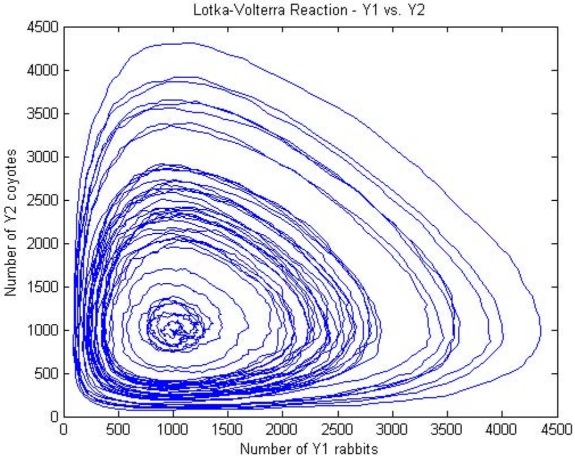
Prey-Predator Systems

- The evolution of a prey-predator systems leads to interesting dynamics
- These dynamics have been encoded in the Lotka-Volterra equation [SB06]
- Depending on the parameters values the system may evolve either to overpopulation, extinction or periodical evolution
- The Lotka-Volterra equation:

$$\frac{dx}{dt} = x(\alpha - \beta y)$$

$$\frac{dy}{dt} = -y(\gamma - \delta x)$$

Lotka-Volterra Equation



A chart depicting the state space defined by the Lotka-Volterra equation

Synchronised Flashing in Fireflies I

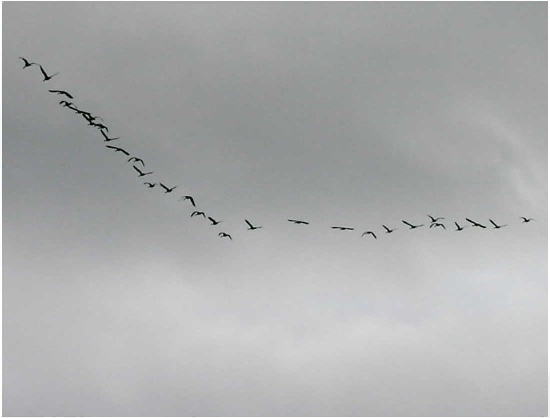
- Some species of fireflies have been reported of being able to synchronise their flashing [CDF+01]
- Synchronous flashing is produced by male during mating
- This synchronisation behaviour is reproducible using simple rules
  - Start counting cyclically
  - When perceive a flash, flash and restart counting

Synchronised Flashing in Fireflies II

Schools of Fishes

School of fishes exhibit coordinated swimming: this behaviour can be simulated based on speed, orientation, and distance perception [CDF+01]

Flocks of Birds



The picture displays a flock of geese: this behaviour can be simulated based on speed, orientation, and distance perception [CDF+01]

Insects Colonies

- Behaviours displayed by social insects have always puzzled entomologist
- Behaviours such as nest building, sorting, routing were considered requiring elaborated skills
- For instance, termites and ants build very complex nests, whose building criteria are far than trivial, such as inner temperature, humidity, and oxygen concentration

Termites Nest in South Africa

The picture displays the Macrotermes michealseni termite mound of southern Africa

Stigmergy

- In a famous 1959 paper [Gra59], Grassé proposed an explanation for the coordination observed in termites societies

  The coordination of tasks and the regulation of constructions are not directly dependent from the workers, but from constructions themselves. The worker does not direct its own work, he is driven by it. We name this particular stimulation stigmergy.

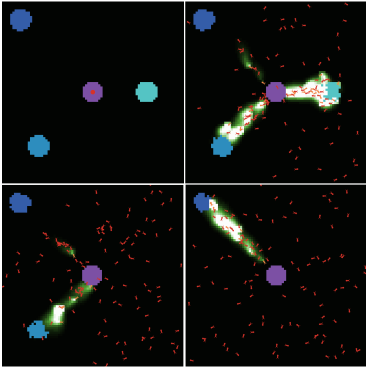
Elements of Stigmergy

- Nowadays, stigmergy refers to a set of coordination mechanisms mediated by the environment
- For instance in ant colonies, chemical substances, namely *pheromone*, act as markers for specific activities
- E.g. the ant trails between food source and nest reflect the spatial concentration of pheromone in the environment

Trail Formation in Ant Colonies

The picture food foraging ants. When carrying food, ants lay pheromone, adaptively establishing a path between food source and the nest. When sensing pheromone, ants follow the trail to reach the food source.

Simulating Food Foraging



The snapshots display a simulation of food foraging ants featuring a nest and three food sources. Ants find the shortest path to each sources ad consume first the closer sources. When no longer reinforced, the pheromone eventually evaporates.

Stigmergy and the Environment

- In stigmergy, the environment play a fundamental roles, collecting and evaporating pheromone
- In its famous book [Res97], Resnick stressed the role of the environment

  The hills are alive. The environment is an active process that impacts the behavior of the system, not just a passive communication channel between agents.

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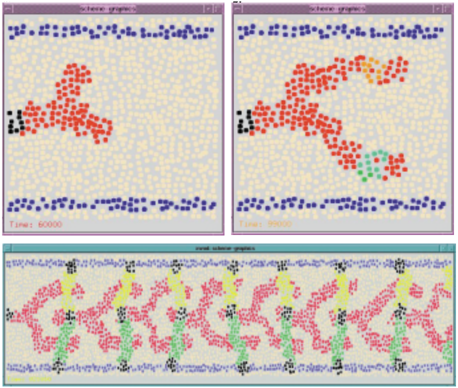
Swarm Intelligence

- *Swarm intelligence* is a problem solving approach inspired by collective behaviours displayed by social insects [BDT99, BT00]
- It is not a uniform theory, rather a collection of mechanisms found in natural systems having applications to artificial systems
- Applications of Swarm Intelligence include a variety of problems such as task allocation, routing, synchronisation, sorting
- In Swarm Intelligence, the most successful initiative is Ant Colony Optimisation

ACO: Ant Colony Optimisation

- ACO [DS04] is a population-based metaheuristic that can be used to find approximate solutions to difficult optimisation problems
- A set of software agents called artificial ants search for good solutions to a given optimisation problem
- To apply ACO, the optimisation problem is transformed into the problem of finding the best path on a weighted graph
- ACO provided solutions to problems such as VRP-Vehicle Routing Problem, TSP-Travelling Salesman Problem and packet routing in telecommunication networks

Amorphous Computing



An amorphous computing [AAC+00] medium is a system of irregularly placed, asynchronous, locally interacting identical computing elements.

Autonomic Computing

- An industry driven research field initiated by IBM [KC03], mostly motivated by increasing costs in systems maintenance
- Basic idea: applying self-organising mechanisms found in human nervous system to develop more robust and adaptive systems
- Applications range from a variety of problems such as power saving, security, load balancing

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Robocup I

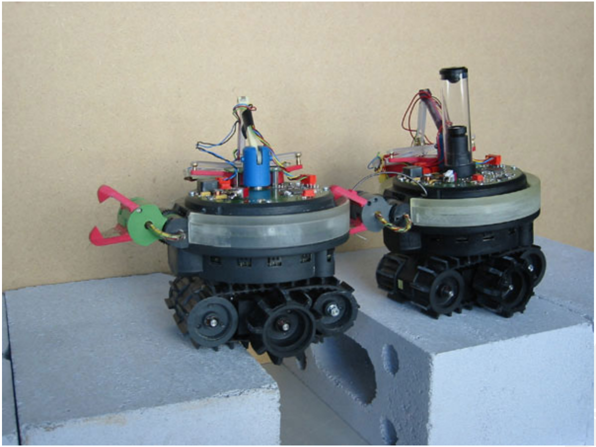
By the year 2050, develop a team of fully autonomous humanoid robots that can win against the human world soccer champion team.

- Robocup objective consists in pushing robotics research applying the techniques developed to eventually win soccer match
- Robocup matches are organised in leagues reflecting different robot capabilities
- Self-organising techniques are extensively applied since the robots have to be autonomous rather than remotely controlled

Robocup II

A few robots participating to Robocup 2006

SWARM-BOTS



SWARM-BOTS [DTM+05] was a project funded by European Community tailored to the study of self-organisation and self-assembly of modular robots.

AGV – Automated Guided Vehicles

- Stigmergy has been successfully applied to several deployments of Automated Guided Vehicles [WSHL05, SMPB05]
- Basically, the AGVs are driven by digital pheromones fields in the same way ants perform food-foraging

Various pictures of AGVs

Outline

Are SOS Autonomous?

- They are *adaptive*, in that they properly respond to external stimuli
- So their autonomy from the environment is *partial*
- At the same time, they are *self-governed*, in that their evolution is self-driven, in some essential sense—it is at least teleonomic
- So, their autonomy is evident, as well

Systems as Agents?

- In the following, we take as understood the fact that the notion of *autonomy* applies to *systems*
- Our implicit assumption is that *users* (generally) and *designers* (at some point) consider a *system as a whole*, and conceive it as such
- that is, as a computational system with its own computational autonomy—which for us means an agent, at a certain level of abstraction

→ this basically means that we can evaluate other notions of autonomy for a system as a whole

How Much Autonomy?

- Good design of a SOS provides the *goals* to be achieved, and the *means* to self-organise the system structure accordingly
- How much autonomy in that?
- How much autonomy
  - from the designer
  - from the user
  - from the environment
  - overall

  ?

Which Autonomy for SOS?

- Self-organising systems (SOS) exhibit some autonomy by definition
  - their evolution over time is not pre-defined by the designer
  - → in this sense, SOS are autonomous with respect to the designer
  - however, any evolution of a well-engineered SOS tends towards the tasks / goals assigned by the designer
  - → in this sense, SOS are not autonomous with respect to the designer
  - their evolution over time is not is influenced by the environment, but is not directly driven by it
  - → in this sense, SOS are autonomous with respect to the environment
- Most of the SOS we know are natural systems, where it is not clear whether one can say that the goals are somehow self-generated
- However, for sure, computational SOS built from those examples are likely to show *executive autonomy*, without *motivational autonomy*

Autonomy of SOS Depends on. . .

- The models, mechanisms, and technologies adopted for implementing computational SOS

! The level of autonomy of a SOS do not depend straightforwardly on the level of autonomy of the agent components

Component vs. System Autonomy

- SOS are systems with some autonomy made of autonomous components
- However, no clear relationship between the sort of autonomy of components and the sort of autonomy of the system can be stated a priori

→ which basically means that autonomy of a SOS does not necessarily rely upon its components only

→ and also means that issues like responsibly and liability require a non-trivial, non-obvious treatment

Outline

MAS 4 SOS

- Is the agent paradigm the right choice for modelling and developing SOS?
- Are agents the right abstractions for SOS components?
- Are MAS the right way to put together components of a SOS?
- In order to answer this question we have to compare requirements for SOS with features of MAS

SOS Requirements

- From our previous discussion on self-organisation and emergence, a possible basic requirements list can be given as follows:
    - *Autonomy* and *encapsulation* of behaviour
    - *Local actions* and *perceptions*
    - *Distributed environment* supporting *interactions*
    - Support for *organisation* and *cooperation* concepts

MAS Checklist

It is easy to recognise that the agent paradigm provides suitable abstractions for each aspect

- Agents for autonomy and encapsulation of behaviour
- Situated agents for local actions and perceptions
- MAS distribution of components, and MAS environment supporting interactions through *coordination*
- MAS support for organisation and cooperation concepts

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